Radiation Environment Near the Sun: Solar Probe

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INTRODUCTION

A panel of scientists and engineers met from 12-14 March 2000, to assess the radiation environment near the sun (energetic protons and ions, relativistic electrons, hard x-rays, γ-rays and neutrons). The purpose of the workshop was to define the radiation peak fluxes and fluences and determine the impacts that these may have on the success of the Solar Probe mission. The Solar Probe spacecraft will pass within 4 R_S of the center of the sun in 2010 (solar maximum) and again in 2015 (solar minimum).

The radiation impacts on Solar Probe are due to transient events. There are two types, "prompt" and "gradual". Prompt events produce energetic proton and heavy ions and relativistic electrons at the base of the corona. These particles are guided by magnetic fields into interplanetary space. The fraction of these particles that go in the other direction, into the low solar atmosphere, produce secondary radiation: γ-rays, x-rays and neutrons.

The largest of these prompt events occur approximately 20-30 times per year during solar maximum. There are approximately ten times less events during solar minimum. Prompt events occur within active regions which are located at 25˚ - 35˚ latitudes at solar maximum. Active regions are located closer to the equator at solar minimum.

Energetic particles are also produced by smaller flares (~3000/year at solar maximum). However, the ion fluxes and fluences are far less than those for the peak events.

Gradual events are associated with fast CME driven shocks. These shocks occur above helmet streamers and avoid coronal holes. This happens because the Alfvén speed is ~100 km s^{-1} above streamers and is > 1,000 km s^{-1} within coronal holes.

The fluxes and fluences of gradual events are dependent on the speed of the fast coronal ejecta. Ejections slower than 400 km s^{-1} will not affect Solar Probe at 4 R_S.

RESULTS

A summary of the results are given in Table 1.

Table 1.

Radiation Type	Maximum Flux $(cm^{-2} s^{-1})$	Maximum Fluence/Event $[cm^{-2}]$
Protons > 10 MeV	10^8	10^{11}
Heavy Ions > 10 MeV/n		
$^4He + {}^3He$	2×10^7	2×10^{10}
C + N + O	3×10^4	3×10^7
Ne + MG + Si	10^4	10^7
Fe	10^4	10^7
Electrons > 1 MeV	10^8	10^{11}
Neutrons $\geq$ 1 MeV	10^7	10^9
Hard X-rays and γ-Rays with E > 50 keV	10^8	10^{10}

Maximum fluxes and fluences correspond to the largest solar flares (rate ~ 1 per year during solar maximum) at 4 solar radii from Sun-center. The data have been scaled by r^{-2} from interplanetary observations made between 0.3 and 1 AU. For neutrons and photons, fluxes were derived from measured fluences assuming a flare duration of 100s. For the charged particles, fluences are derived assuming a flare duration of 1000s (note: flare durations in hard electromagnetic radiation indicate acceleration lasting between 100 and 1000s. Going from observations to extrapolation, we use the limit which led to the largest, most conservative numbers).

Radiation Effects

Below is a summary of the dominant radiation effects that can occur on a spacecraft. Further information can be found in "Handbook of Radiation Effects" by A. Holmes-Siedle and L. Adams, Oxford University Press, 1993.

<u>TID - Total Ionizing</u> Dose

Caused by charge deposition in the semiconducting device. The result of TID is device parametric degradation (e.g, V_{th} shifts, I_{in} leakage increases). In the worst-case, some devices will fail functionally without observable significant parametric degradation.

Devices that fail parametrically, as determined by radiation characterization or radiation lot acceptance tests (RLAT), can be used as long as parametric degradation is accounted for in the worst-case circuit analysis. Devices that fail functionally, especially those that fail at a dose $\leq$ mission requirement should be avoided.

<u>DD - Displacement Damage</u>

Displacement damage is caused by "billiard ball" collisions between incident protons or neutrons (electrons also contribute to this effect but require ~10x larger fluence) and the semiconductor crystal lattice. The displacement, or dislocation, of the crystalline lattice in the semiconductor causes parametric shifts in the device's performance characteristics. Radiation's ability to cause this type of damage is sometimes quantified in terms of its non-ionizing energy loss (NIEL) in the device. As with TID, this effect also requires characterization as part of the RLAT, to account for this degradation in the worst-case circuit analysis.

<u>SEU - Single Even Upsets</u>

There are several types of effects that can be caused by passage of single high-energy particle through an electronic device. As a group, they are referred to as single event effects, or SEEs.

SEUs are caused primarily by heavy ion strikes (although some very sensitive devices are upset by protons) in a semiconducting device that contains storage elements (e.g., flip flops memory cells). The result is a change in state (1 to 0 or 0 to 1) of the storage element. This state will remain until the storage element is re-written (e.g., next clock edge for the flip flop, EDAC in memory). There are typically 2 methods of accounting for SEUs; calculation of the device upset rate (cell upsets over entire device) and calculation of the probability of experiencing an upset for a given time period (e.g., 1% of the 10 min. period). For an assembly, one adds up the upset rate or probabilities of all the devices with storage elements in the assembly, yielding the assembly upset rate. To perform these calculations, one needs the LET (linear energy transfer in MeV-cm^2/mg) vs. cross-section curve for the device. This is

accomplished by testing in a heavy ion accelerator. This information with the mission's heavy ion environment, usually expressed as ion LET vs. ion flux, is used to calculate the upset rate, or upset probability, for a given device.

SET – Single Event Transient

SETs are caused by electron-hole generation in a semiconductor device as a result of incident protons or electrons (neutrons may also contribute but to a lesser degree). This causes a transient pulse to appear at the device's output. If the pulse width and height are large enough for the load device to respond, the transient will propagate through the circuit causing erroneous circuit function. The SET rate is a function of the proton or electron flux and the device's susceptibility.

Mitigation is accomplished by device selection, characterization (heavy ion accelerator) and signal line filtering.

SEL – Single Event Latchup

SELs are caused by heavy ion strikes in CMOS devices. The ion creates a current in the substrate, thereby activating the substrate SCR (silicon controlled rectifier, an attribute of CMOS fabrication) resulting in excessive current flow causing either functional failure or catastrophic device burnout (from thermal runaway). This effect is considered catastrophic, and hence, is mitigated by selection of devices that are "immune" (i.e., LET threshold $\geq$ 75 MeV-cm^2/mg).

SEDR – Single Event Dielectric Rupture

SEDRs are caused by heavy ion strikes in CMOS devices and power HEXFETs. The ion path through the semiconductor creates a discharge path for the electric field through the gate dielectric resulting in the rupture of the gate dielectric. The effect is considered catastrophic, and hence, requires characterization in a heavy ion accelerator, and in the application of HEXFETs, V_{DS} derating in the circuit application.

SEB – Single Event Burnout

SEBs are caused by heavy ion strikes in power bipolar transistors. The ion path through the semiconductor creates a discharge path for the electric field through the collector-base or base

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emitter junctions resulting in the burnout of the device. The effect is considered catastrophic, and hence, requires characterization in a heavy ion accelerator and V_{CE} derating in the circuit application.

Flux Rate Sensitive Devices

This effect is commonly a concern for imaging detectors (IR, UV, visible). The rate of particle impingement on the sensor can cause increased noise in the detector which often can be filtered out algorithmically. However, the sensor should be characterized in a proton or electron accelerator for proper characterization.

PD – Prompt Dose

PDs are caused by extremely high flux of either electrons, protons, or x-and gamma-rays. The resultant flux creates electron-hole pairs causing large currents to flow in the semiconducting device. This results in either erroneous part function or complete device burnout. This effect is mitigated by characterization and proper part selection. It is unlikely that the near-sun radiation environment will cause this effect.

Mitigation of Environmental Hazards

A number of strategies are employed to mitigate the effects of the above hazards.

Design Rules (TID & Displacement Damage)

The degradation effects must be accounted for in the design. At the end of the mission, the accumulated effects should not affect the performance of the electronics. To accomplish this, the final parametric degradation effects must be used in the worst-case circuit analysis. In addition, a Radiation Design Margin (RDM) is used to cover uncertainties in the environment.

Shielding (TID & Displacement Damage)

Shielding is used to reduce the effect of the TID and Displacement Damage environment. Standard designs use aluminum but under severe conditions, tungsten is used. Local or spot shielding is preferred when a limited number of "soft" or susceptible parts are required to meet a design function. Individual or similarly tolerant parts are placed in close proximity to take

advantage of in-situ or design shielding. Thus, transport analysis may indicate preferential placement within an assembly or circuit card.

Single Event Effects

For mitigation against SEUs, SETS a designer can use the following techniques:

- Watchdog timers to detect and correct software deviations from expected flow.

- Error detection and correction algorithms when reading stored words.

- Triple-storage single-bit data and use majority voting to determine value on readout.

To mitigate against SEL use latchup resistant electronics, or use current-limiting and current-detecting circuitry to cycle power to the device. The latter technique requires extensive latchup characterization and careful circuit design. For high reliability missions this technique is not recommended.

To mitigate against SEDR or SEB use SEDR or SEB immune electronics or characterize the V_{DS} or V_{CE} failure voltage in a heavy ion accelerator. Derate the failure voltage in the circuit application.

ESD (Electrostatic Discharge)

Surface charging is mitigated by ensuring that all surfaces of the spacecraft are conductive and electronically connected. This keeps potential differences from building up across different parts of the spacecraft, so that arcing will not be initiated across the surface of the spacecraft.

*Buried Charging occurs deep inside the spacecraft, on piece parts and circuit boards and is mitigated by minimizing the volume and area of insulators within the spacecraft.

Prompt Dose, EMP

These effects are unlikely to be a concern for Solar Probe.

CONCLUSIONS

Based on the flux and fluence levels of Table 1, and assuming a power-law dependence of E^{-3} in the integral spectra, the doses and dose rate levels behind 1 mm of aluminum shielding are given in Table 2.

Table 2.

Radiation Type	Maximum Dose Rate (rad Si s^{-1})	Maximum Dose/Event (rad-Si)
Protons	40.	4 x 10^4
Heavy Ions > 10 MeV/n ^{4}He + ^{3}He C + N + O Ne + Mg + Si Fe	~ 0. (SEE only)	~ 0. (SEE only)
Electrons	3.	3 x 10^3
Neutrons ≥ 1 MeV	~0. (NIEL only)	~0. (NIEL only).
Hard X-rays and γ-Rays with E > 50 keV	10^{-2}	1.

These ionizing-dose and NIEL contributions to the mission's cumulative radiation exposure are less than other sources of radiation, and are not large enough to seriously impact the spacecraft design. The Solar Probe mission requires a flyby of Jupiter to take the spacecraft out of the ecliptic plane, during which it is estimated to receive 100 kilorad behind 1 mm of aluminum. The Radioisotrope Thermal Generator power source is estimated to expose electronics to the equivalent of 10^{11} 1-MeV neutrons in the course of the mission. These radiation levels are not trivial, but are within current spacecraft design capabilities.

More work is needed to fully understand the design implication of the heavy ion flux. The flux level is high, though not necessarily overwhelming. One should also recall that this flux is only expected to occur about once every year.